ELFE : an Electron Laboratory for Europe.

Christian Cavata[a] and Bernard Pire[b]

a) DAPNIA, Centre d'Etudes Nucléaires de Saclay, 91191 Gif sur Yvette, France.
b) Centre de Physique Théorique, Ecole Polytechnique, F-91128 Palaiseau, France.

Abstract

This paper presents a brief overview of the physics with the 15-30 GeV continuous beam electron facility proposed by the European community of nuclear physicists to study the quark and gluon structure of hadrons.

Résumé

Cet article présente un bref survol du domaine de physique pour lequel la communauté européenne de physique nucléaire vient de recommander de construire un accélérateur d'électrons de 15 à 30 GeV à faisceau continu. La question centrale étudiée grâce à cette machine sera la structure en quarks et gluons des hadrons.

1. Introduction

Recently, the Nuclear Physics European Collaboration Committee (NuPECC) of the European Science Foundation has recommended [1] the construction of a 15-30 GeV high intensity continuous beam electron accelerator. The goal of this new facility is to explore the quark structure of matter by exclusive and semi-inclusive electron scattering from nuclear targets.

In the last two decades, we have seen the emergence of a theory that identifies the basic constituents of matter and describes the strong interaction [2]. The elementary building blocks of atomic nuclei are colored quarks and gluons. The theory describing their interactions is Quantum Chromodynamics (QCD) which has two special features, asymptotic freedom and color confinement. Asymptotic freedom means that color interactions are weak at short distances. At large distances, color confinement results in the existence of hadrons and in the impossibility to observe quarks and gluons as single particles.

Although one knows the microscopic theory for the strong interactions, *one does not understand how quarks build up hadrons.*

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2. The ELFE project

The ELFE research program[3],[4] lies at the border of nuclear and particle physics. Most of the predictions of QCD are only valid at very high energies where perturbation theory can be applied. Understanding however how hadrons are built, is the domain of confinement where the coupling is strong. Up to now there are only crude theoretical models of hadronic structure inspired by QCD. One hopes that in the next ten years major developments of nonperturbative theoretical methods such as lattice gauge theory will bring a wealth of results on the transition from quark to hadron. However, many theorists think that it is fundamental to guide theory with accurate, quantitative and interpretable measurements obtained by electron scattering experiments.

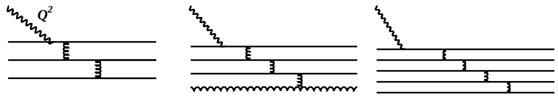

Figure 1. Hard scattering amplitudes for the proton form factor. $1/Q^2$ expansion

The research program of ELFE addresses the questions raised by the quark structure of matter: the role of quark exchange, color transparency, flavor and spin dependence of structure functions and differences between quark distributions in the nucleon and nuclei, color neutralization in the hadronization of a quark... All these questions are some of the many exciting facets of the fundamental question:

"How do color forces build up hadrons from quarks and gluons? "

ELFE will focus on the following research topics:

- **Hadron structure** as revealed by hard exclusive reactions : baryon form factors, real and virtual Compton scattering, electro and photo-production of mesons (π,K,ρ,ϕ ...), meson (π,K, ...) form factors.
- **Evolution from mini-hadron to hadron** in Color Transparency experiments.
- **Vector mesons and heavy quarks** : diffractive production and exclusive scattering at high transfers.
- **Space time picture of quark hadronisation** through the study of absorption by nuclear medium.
- **Separation of Valence and Sea** content of the proton by tagged structure functions measurements.
- **Study of spin structure** of the nucleon through semi-inclusive experiments.
- **Light nuclei short distance structure** through form factor measurements and deep inelastic scattering at $x > 1$.

We will here concentrate on exclusive reactions. The concept and experimental situation of color transparency have been presented elsewhere [5]. Hadronization and tagged structure functions are already classical fields of QCD, but they should be an important part of the ELFE program because of the specific parameters foreseen for the machine.

3. Hard Exclusive reactions: A new tool

Exclusive reactions[6] are processes in which the final state is completely resolved. They are important since at high momentum transfers they select the simplest non perturbative objects. This is what we will now explain.

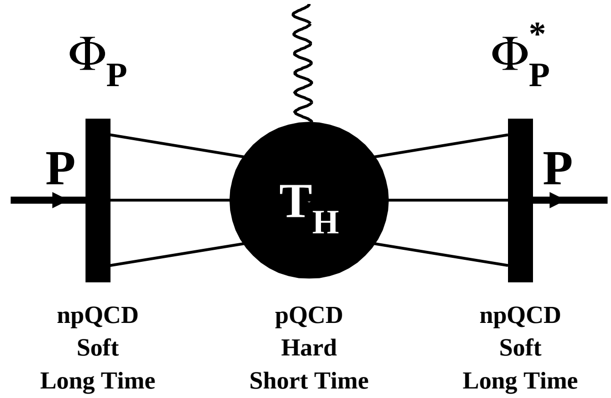

Figure 2. The factorization of a hard scattering amplitude

3.1. Factorization and Valence selection

Perturbative QCD studies have shown that factorization properties allow to separate well-defined non perturbative objects which are crucial for the understanding of confinement dynamics from perturbatively calculable hard processes.

One starts with the Fock expansion[7] with a fixed number of quarks and gluons for a proton state of momentum P :

$$|P> = \Psi^P_{qqq}|qqq> + \Psi^P_{qqq,g}|qqq,g> + \Psi^P_{qqq,q\bar{q}}|qqq,q\bar{q}> + ...$$

where $\psi^P_l(x_i, \vec{k}^\perp_i)$ describes how the l quarks and gluons share the proton momentum. The wave functions Ψ^P_l are functions of light-cone momentum fraction x_i, transverse momentum $k^\perp_i$ and helicities. They contain the information on quark confinement dynamics. Here the quarks are "current" quarks and not "constituent" ones.

A constituent quark may be seen as a complex structure consisting of a current quark "dressed" of quark-antiquark pairs and gluons. Constituent quarks are important to get an intuitive picture of the quark structure of the nucleon, but they cannot be used to understand quark dynamics in the framework of a relativistic quantum field theory.

Of particular interest is Ψ^P_{qqq}, the valence proton wave function. This is the simplest non perturbative object in the proton.

Let us take the example of the proton form factor. As depicted on figure 1, the "three quarks" hard scattering amplitude gives a contribution to the form factor proportional to $\left[1/Q^2\right]^2$ due to the two gluon propagators, whereas the "3 quarks 1 gluon" amplitude, requiring three gluon propagators, contributes for $\left[1/Q^2\right]^3$. The argument may be repeated for more participating constituents and for any reactions. Thus,

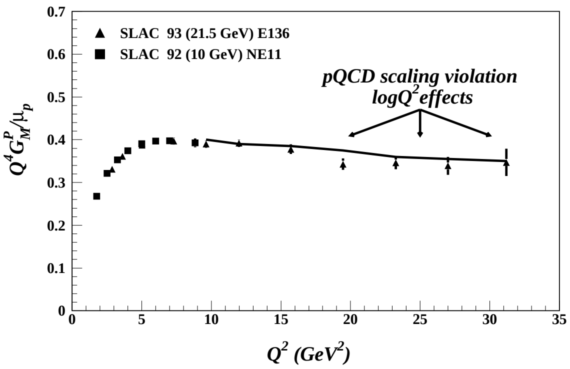

Figure 3. Q^2 evolution of the proton form factor. Above 10 GeV^2, Scaling is established.

the valence component ϕ^P_{qqq} turns out to be the dominant one in hard exclusive reactions.

Factorization is then the statement that a hard matrix element can be written as (see Figure 2)

$$< P|T|P > \simeq \phi^{*P}_{qqq} \otimes T_H^{qqq,qqq} \otimes \phi^P_{qqq}, \tag{1}$$

up to $1/Q^2$ corrections. Integrals over momentum fractions x_i and y_j are implicit. Here

$$\phi_{qqq}(x_i) = \int [dk^\perp]\psi_{qqq}(x_i, \vec{k}_i^\perp)$$

is the proton Valence Distribution Amplitude, and $T_H^{qqq,qqq}$ is a hard scattering amplitude, calculable in perturbative QCD.

The applicability of this factorization in a definite energy domain is indicated by some definite statements, such as the logarithmically corrected dimensional counting rules, the helicity conservation law and the appearance of color transparency. The few data available [8] (see figure 3) indicate that the ELFE parameters indeed correspond to this well defined physics domain. Nevertheless, checking factorization will be a necessary prelude of the experimental program at ELFE.

Configurations of small transverse extension are also selected by hard exclusive reactions. Indeed, in the Breit frame where the virtual photon is collinear to the incoming proton which flips its momentum, the first hit quark changes its direction and gets a momentum $O(Q)$; it must transmit this information to its comovers within its light cone; this can only be achieved if the transverse separation is smaller than $O(1/Q)$. This is the basis of the Color Transparency phenomenon.

3.2. QCD evolution of wave functions

The analysis of QCD radiative corrections to any exclusive amplitude has shown [7] that the factorized distribution amplitudes obey a renormalization group equation, leading to a well understood evolution in terms of perturbative QCD. At asymptotic Q^2, the distribution amplitudes simplify, e.g. for the proton valence distribution amplitude:

$$\phi^P_{qqq}(x_1, x_2, x_3, Q^2) \rightarrow 120x_1x_2x_3\delta(1-x_1-x_2-x_3) \tag{2}$$

The Q^2 evolution is however sufficiently slow for the distribution amplitude to retain much information at measurable energies on confinement physics. The experimental strategy of ELFE physics is thus to sort out the hadron distribution amplitudes from various exclusive reactions to learn about the dynamics of confinement.

At finite Q^2 the proton valence wave-function can be written as a series derived from the leading logarithmic analysis, in terms of Appel polynomials $P_i(x_i)$, as [7]

$$\begin{aligned}\phi^P_{qqq}(x_i, Q^2) = 120x_1x_2x_3 \{ \, 1 + \tfrac{21}{2}\left(\frac{\alpha_S(Q^2)}{\alpha_S(Q_0^2)}\right)^{\lambda_1} A_1P_1(x_i) \\ + \tfrac{7}{2}\left(\frac{\alpha_S(Q^2)}{\alpha_S(Q_0^2)}\right)^{\lambda_2} A_2P_2(x_i) + ... \, \} \, .\end{aligned} \tag{3}$$

The unknown coefficients A_i are governed by confinement dynamics.

3.3. A strategy for data analysis

A first way to analyse data is to compare experimental points to a calculation with a given distribution amplitude that any prejudiced theorist convinced you to choose.

A more model-independent way is to try to sort out the wave function directly from the data. Let us outline a possible strategy on the example of real Compton scattering. Using the expansion of Eq. 3, we write the Compton differential cross-section as a sum of terms

$$A_iT_H^{ij}(\theta)A_j$$

where T_H^{ij} are integrals of the hard amplitude at some given scattering angle θ multiplied by the two Apple polynomials $A_i(x)$ and $A_j(y)$ integrated over light-cone variables x and y. The analytical expression is complicated but can easily be electronically managed.

Sorting out the valence wave function of the proton from the data amounts then to determine through a maximum of likelyhood method the parameters A_i restricting to something like ten terms in the expansion of Eq. 3. A direct test of the validity of the approach is then to explore both real and virtual Compton scattering data at all angles which should be understood with the same series of A_i's.

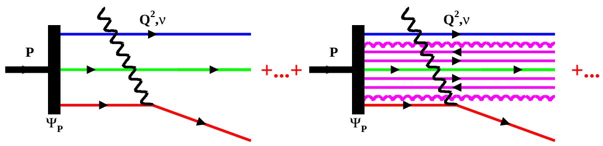

Figure 4. Proton structure as seen by DIS experiments

3.4. Other processes

Photo- and electro-production of mesons at large angle will enable to probe π and ρ distribution amplitudes in the same way. The production of $K\Lambda$ final states will enable to explore strange quark production, for which the diagrams in the hard process are more restricted. Not much theoretical analysis of these possibilities has however been worked out except under the simplifying assumptions of the diquark model [9],[10].

3.5. Deep Inelastic Scattering and Nucleon Wave function

Nearly all existing data on quark distributions in hadrons have been obtained by *inclusive scattering* of high energy particles. In such reactions, one strikes quarks with considerable momentum and energy and reconstructs quark distributions from scattering data. This is possible due to the factorization. This property has given a firm basis for the partonic description, thereby allowing to go beyond the original model proposed by Feynman and Bjorken. Inclusive scattering amounts to an average over all the possible quark configurations in the nucleon (Figure 4). Indeed, the extraction of structure functions in DIS experiments gives access to parton densities $q_{a/P}$ of type a in a proton. For instance the F_2 structure functions is

$$F_2(x,Q^2)=\sum_a e_a^2 x q_{a/P}(x,Q^2).$$

In terms of wave functions, these "parton densities" are

$$q_{a/P}(x,Q^2)=\sum_l \int [dx][dk^\perp]|\Psi_l(x_i,k_i^\perp)|^2\delta(x_a-x)$$

For instance for the u quark,

$$\begin{array}{rllll} u_{a/P} = & \int[dx][dk^\perp] & |\Psi_{uud}|^2 & \delta(x_u-x) & + \\ & \int[dx][dk^\perp] & |\Psi_{uudg}|^2 & \delta(x_u-x) & + \\ & \int[dx][dk^\perp] & |\Psi_{uudgq\bar{q}}|^2 & \delta(x_u-x) & + \quad ... \end{array}$$

By contrast with exclusive reactions, there is no valence wave function selection. In addition to fundamental tests of QCD, the measurements of structure functions have lead to the discovery of the importance of gluons in the momentum and spin distributions in the proton. We now need to go beyond and to understand how simple quark configurations are controlled by confining mechanisms. One needs a different type of data sensitive to the time evolution of a system of correlated quarks. This is the domain of exclusive reactions where scattered particles emitted in a specific channel are observed in coincidence.

Due to the smallness of exclusive amplitudes at large transfers, existing high energy electron accelerators, designed to study electroweak physics, cannot give access to these distribution amplitudes. The only way to study exclusive reactions at large transfer is to use a dedicated high intensity continuous beam accelerator.

4. Accelerator and detectors

The choice of the energy range of 15 to 30 GeV for the ELFE accelerator is fixed by a compromise between

- Hard electron-quark scattering: one must have sufficiently high energy and momentum transfer to describe the reaction in terms of electron-quark scattering. The high energy corresponds to a very fast process where the struck quark is quasi-free. High momentum transfers are necessary to probe short distances.
- The smallness of the exclusive cross sections when the energy increases, as exemplified by the quark counting rules [7].

Beam Energy	$15 \div 30 GeV$
Energy Resolution FWHM	3×10^{-4} @ 15 GeV
	10^{-3} @ 30 GeV
Duty Factor	$\simeq$ 100 %
Beam Current	$10 \div 50\mu$A
Polarized Beams	$P > 80$ %

Table 1. ELFE Accelerator Parameters

Exclusive and semi-inclusive experiments are at the heart of the ELFE project. To avoid a prohibitively large number of accidental coincident events a high duty cycle is imperative. The ELFE experimental program also requires a high luminosity because of the relatively low probability of exclusive processes. Finally a good energy resolution is necessary to identify specific reaction channels. A typical experiment at 15 GeV (quasielastic scattering for instance) needs a beam energy resolution of about 5 MeV. At 30 GeV the proposed experiments require only to separate pion emission. These characteristics of the ELFE accelerator are summarized in table 1.

Due to the very low duty cycle available at SLAC and HERA (HERMES program) one can only perform with these accelerators inclusive experiments and a very

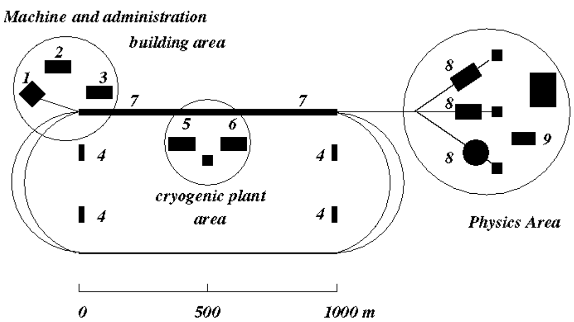

Figure 5. ELFE original design

limited set of exclusive experiments.

ELFE will be the first high energy electron beam beyond 10 GeV
with both high intensity and high duty factor.

The design proposed in 1992 for the machine[3] consists of a 1 km superconducting 5 GeV linac, with three recirculations (figure 5). Taking into account the improvement of cavity performances, and running at 70 % duty cycle would result in a price of order 200 MECU. Different designs could also be considered as for instance, a solution which would combine a test linac of 30 GeV with 1 % duty cycle for the future e^+e^- collider (TESLA) and the existing HERA ring for stretching the pulse. The various components of the ELFE experimental physics program put different requirements on the detection systems that can be satisfied only by a set of complementary experimental equipment. The most relevant detector features are the acceptable luminosity, the particle multiplicity, the angular acceptance and the momentum resolution. High momentum resolution (5×10^{-4}) and high luminosity (10^{38} nucleons/cm^2/s) can be achieved by magnetic focusing spectrometers. For semi-exclusive or exclusive experiments with more than two particles in the final state, the largest possible angular acceptance ($\sim 4\pi$) is highly desirable. The quality and reliability of large acceptance detectors have improved substantially in the last two decades. The design of the ELFE large acceptance detectors uses state of the art developments to achieve good resolution and the highest possible luminosity.

5. CONCLUSIONS

The ELFE research program lies at the border of nuclear and particle physics. Most of the predictions of QCD are only valid at very high energies where perturbation theory can be applied. In order to understand how hadrons are built, however, one has to go in the domain of confinement where the coupling is strong. It is fundamental to guide theory by the accurate, quantitative and interpretable measurements obtained by electron scattering experiments, in particular in exclusive reactions.

This research domain is essentially a virgin territory. There are only scarce experimental data with poor statistics. This lack of data explains to a large extent the slow pace of theoretical progress. The situation can considerably improve due to technical breakthroughs in electron accelerating techniques. We believe that future significant progress in the understanding of the evolution from quarks to hadrons will be triggered by new information coming from dedicated machines such as the ELFE project.

The goal of the ELFE research program, starting from the QCD framework, is to explore the coherent and quark confining QCD mechanisms underlying the strong force. It is not to test QCD in its perturbative regime, but rather to use the existing knowledge of perturbative QCD to determine the reaction mechanism and access the hadron structure.

ELFE will use the tools that have been forged by twenty years of research in QCD, to elucidate the central problem of color interaction: color confinement and the quark and gluon structure of matter.

Aknowledgements

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